Power Generation and Alternative Energy Branch

US Army RDECOM CERDEC CP&ID Power Division
Aberdeen Proving Ground, MD

PGAE - TR – 11 – 15

Hybrid Vapor Compression Ejector Cycle: Presentation to IAPG Mechanical Working Group

Parmesh Verma and Tom Radcliff, United Technologies Research Center

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PGAE - TR – 11– 15 Hybrid Vapor Compression Ejector Cycle

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14. ABSTRACT
An overview of the hybrid vapor compression ejector heat pump cycle developed under an American Recovery and Reinvestment Act funded contract is provided.

15. SUBJECT TERMS
environmental control unit; ejector heat pump; vapor compression cycle

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Communications-Electronics Research Development and Engineering Center

Hybrid Vapor Compression Ejector Cycle

Final Review

Parmesh Verma and Tom Radcliff

Aug. 2011

United Technologies Research Center – East Hartford, CT

Outline

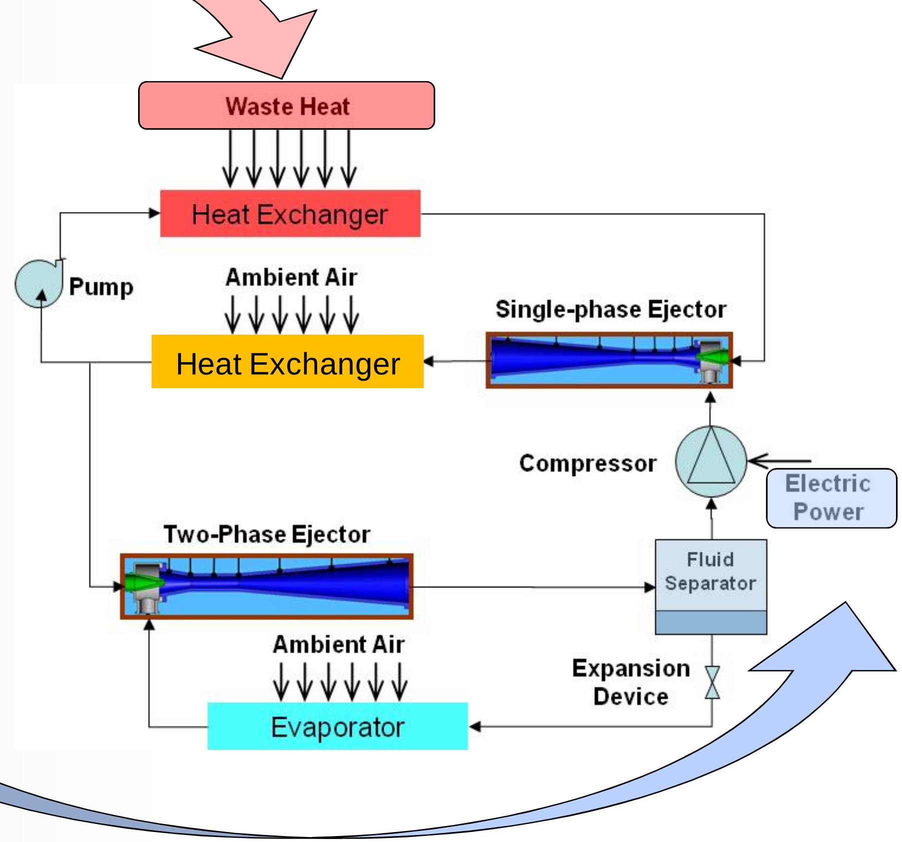
CO_2 Hybrid Vapor Compression Ejector Cycle

- ***System Overview***
- ***Component and System Design***
- ***Integrated Controls***
- ***Fabrication and Testing: Advance Technology Demonstrator (ATD)***
- ***Plan***

System Overview

Objective: *Design, develop & demonstrate a CO_2 5TR (@ 125F ambient) environmental control unit (ECU) using ejector top & bottom cycles*

Deliverables: *+10% η_{system} vs. R410A (baseline); ATD; and reduced-order design tools*



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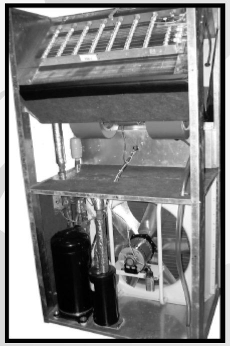
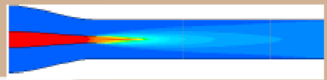
Development Process

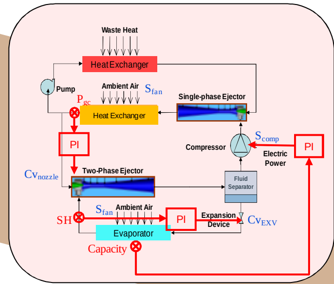
Model based process used to optimize system configuration and component design



✓Key System Requirements
(Heat recovery; 125 F/90F)



✓Component Design & Analysis



✓System Performance and Controls Analysis

✓ATD fabrication and commissioning

Testing and Validation

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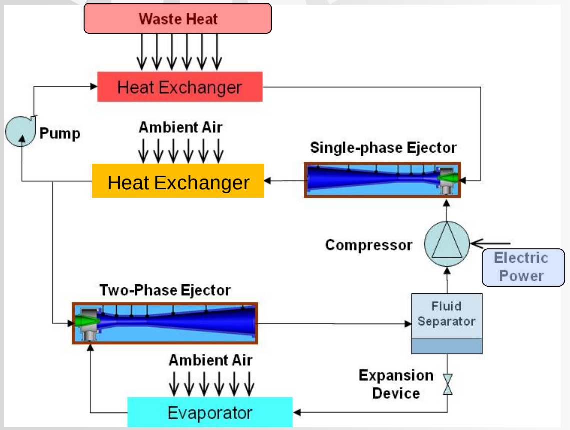
ATD and Models

System and Component Design

Steady-state system model developed in EES and used to design components

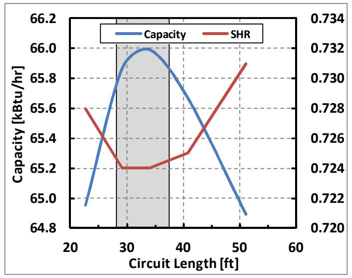
System Modeling and Analysis



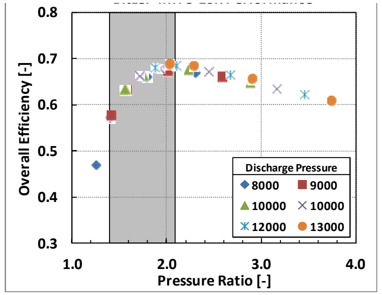
System Schematic

System modeled in EES

Component Design



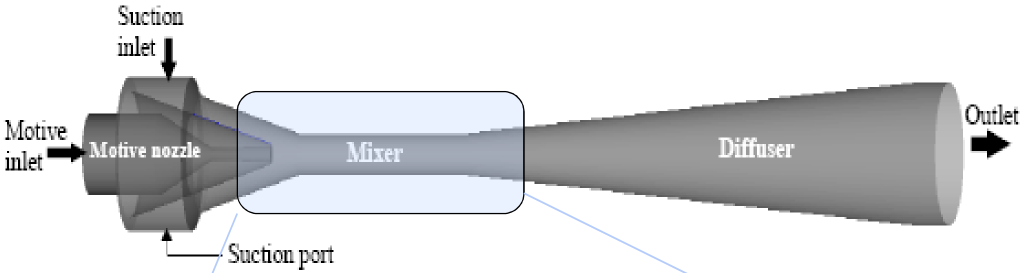
Heat Exchanger

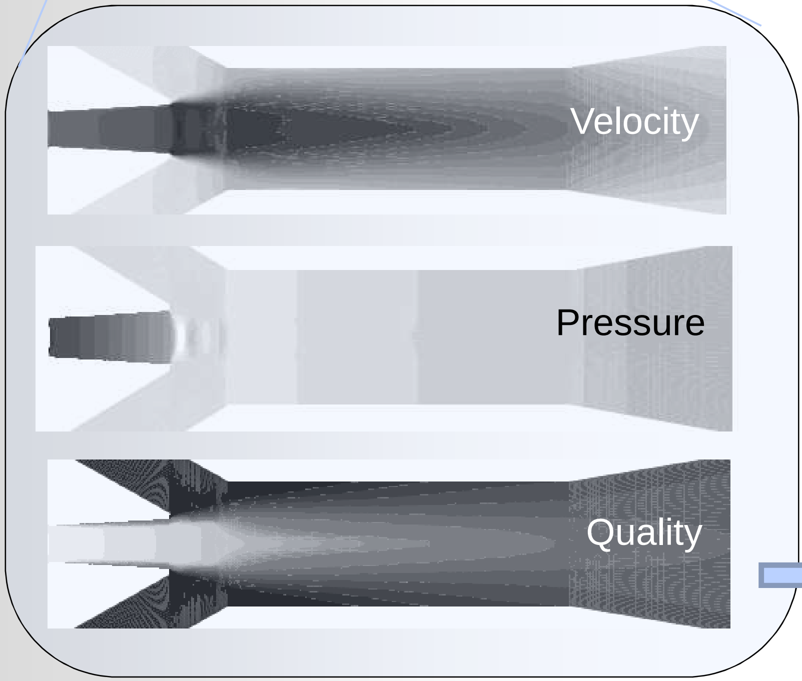


Compressor

Work Recovery Ejector Design

Physics based CFD model developed and validated against multiple experimental data used to design work recovery ejector





Bubble growth: inertial and thermal

$$\dot{m}_{\text{cav},e} = C_e \frac{\sqrt{k}}{\sigma}\rho_l \rho_v \left[\frac{2}{3}\frac{P_v - P}{\rho_l}\right]^{1/2} (1 - \chi_v - \chi_g)$$

$$\dot{m}_{\text{boil}} = \pm \left[\frac{\hat{\sigma}}{2 - \hat{\sigma}}\right] \left(\frac{M}{2\pi R T_{\text{sat}}}\right)^{1/2} [P - P_v]$$

Drift-flux phase slip

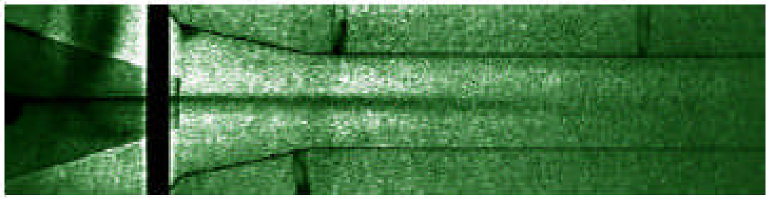
$$\mathbf{v}_{dr,p} = \mathbf{v}_{pq} - \frac{1}{\rho}\alpha_k (\rho \mathbf{v}_q)_k$$

2-phase sonic speed

$$\frac{1}{\rho c^2} = \frac{\alpha_v}{P}\left[(1 - \epsilon_v) f_v + \epsilon_v g_v\right] + \frac{1 - \alpha_v}{P}\epsilon_l g_l$$

Model equations as published in International Journal of Heat and Mass Transfer (v.55, 2012)

Neutron image validation



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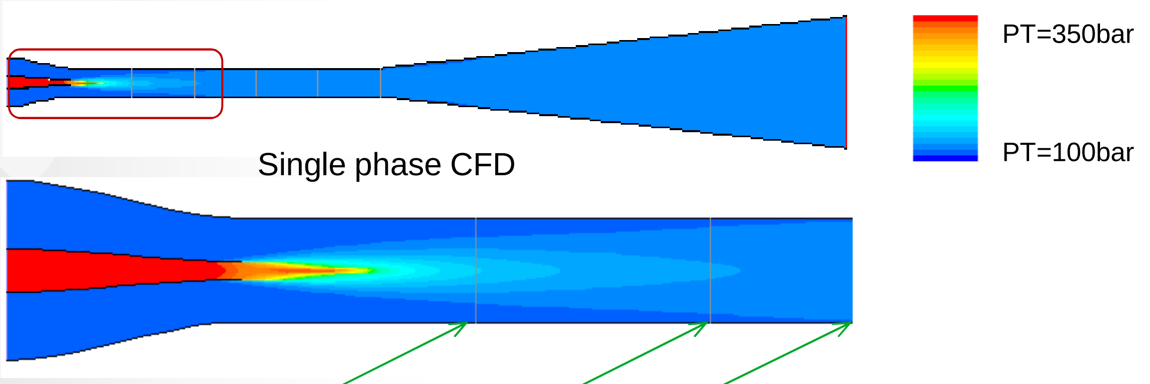
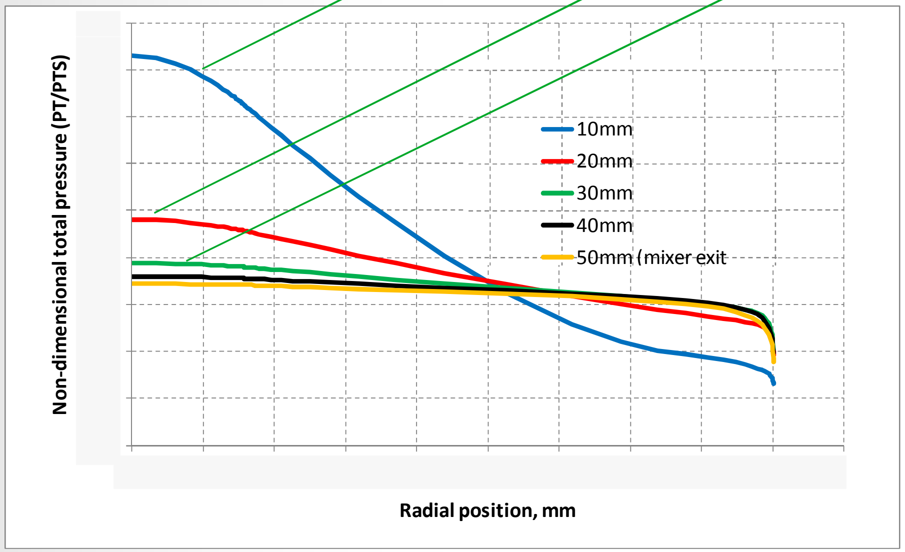
Heat Recovery Ejector Design

Mixing limits design but simulation can be used to investigate new alternatives

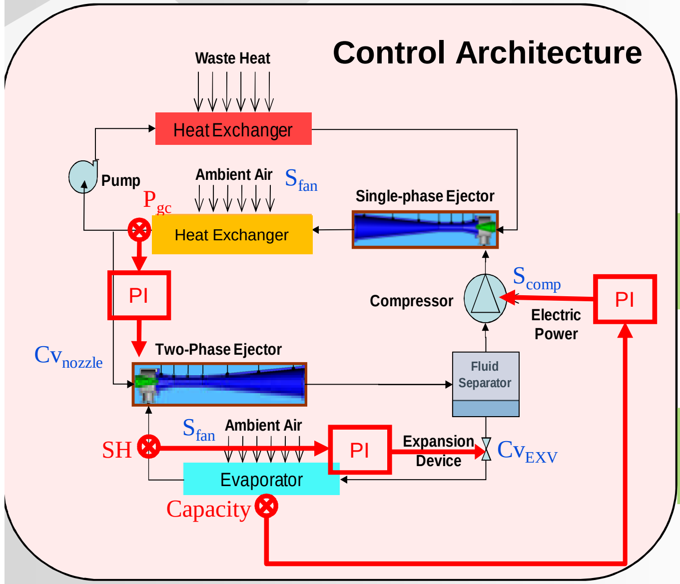




Motive momentum dissipates through turbulence too early
in the mixing process when entrainment ratio is very high

Integrated Controls

Automatic synchronization of three loops to maximize system efficiency

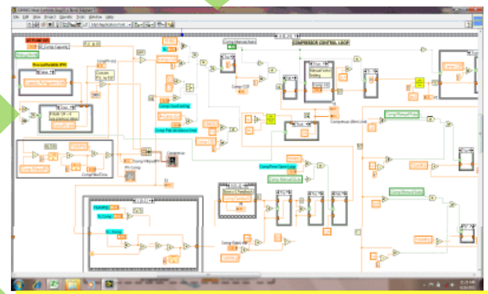


Actuator	Controlled variable
Compressor	Capacity
Ejector	Gas cooler pressure
EXV	Superheat
Gas cooler fan	Indirectly for COP

✓ Component constraints

✓ Set points (EES, steady state)

✓ Controls tuning & closed-loop simulation

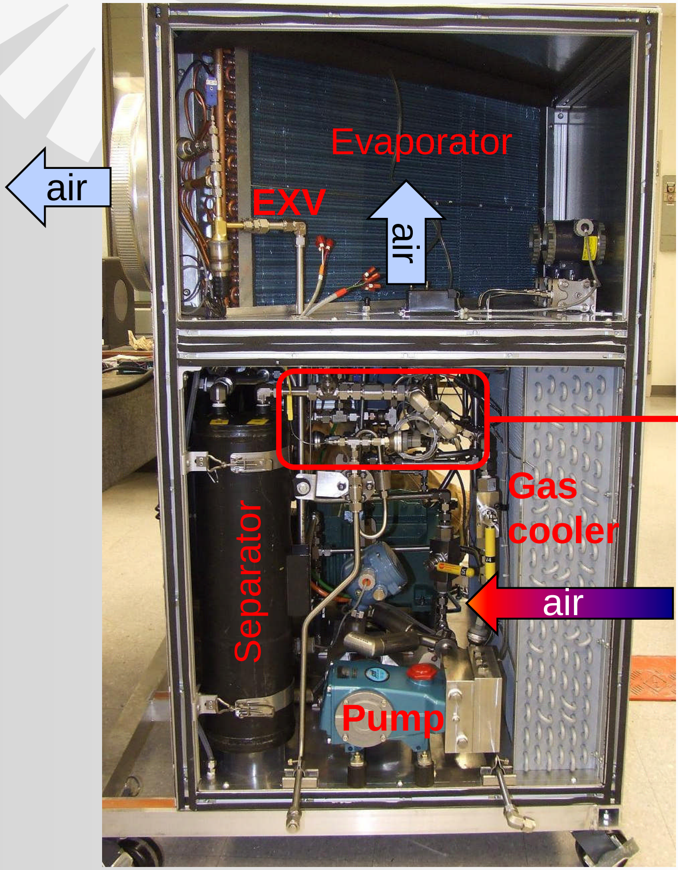


✓ Implementation (LabView)

✓ Control Performance Verification

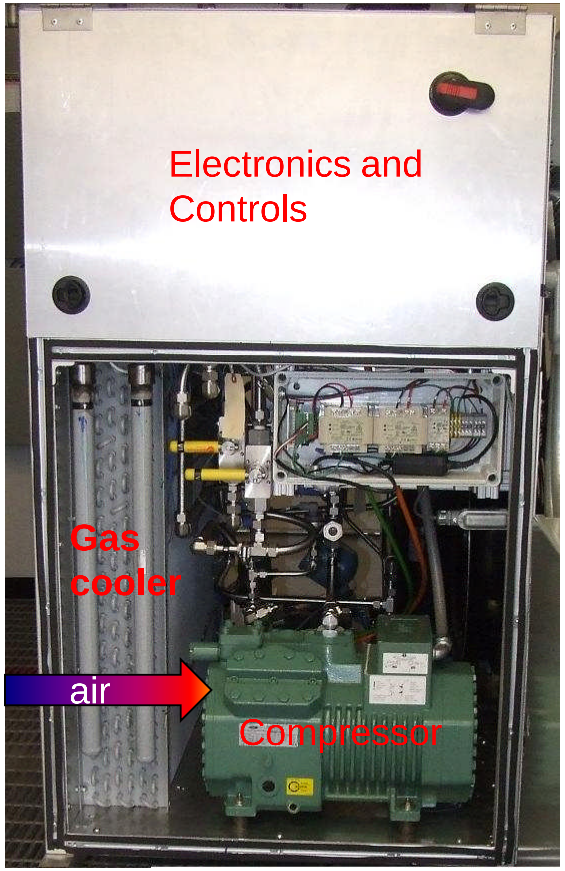
Advance Technology Demonstrator (ATD)

Advance technology demonstrator fabricated



Heat and work recovery ejectors

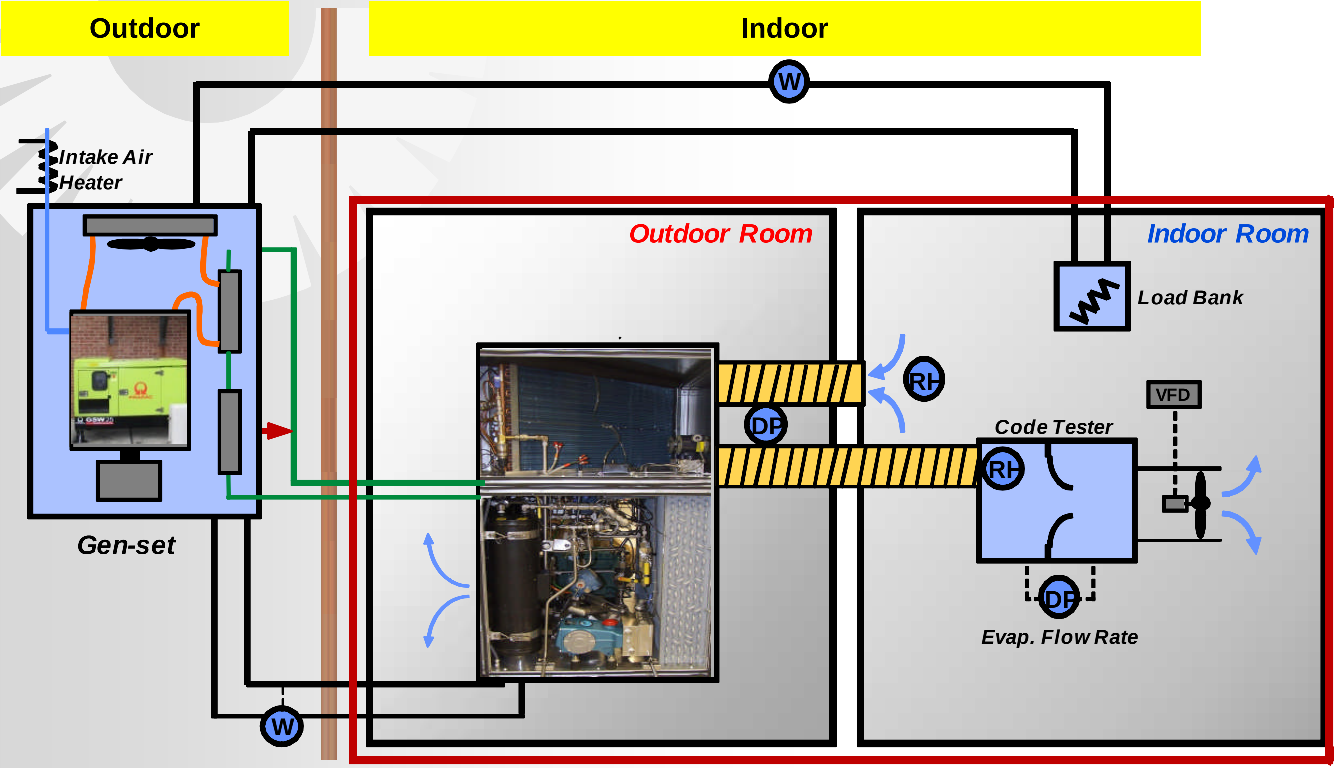
Back



Front

Advance Technology Demonstrator (ATD)

ATD commissioned at Psychrometric Facility



Facility schematic

UTRC Psychrometric Facility

Test Conditions for Indoor and Outdoor rooms			
Test Conditions	Indoor Room		Outdoor Room
	Dry bulb (°F)	Dew Point (°F)	Dry bulb (°F)
ARI B	80	60.3	82
ARI A	80	60.3	95
Army 125	90	75	125

Tested 3 modes:

simple cycle, work recovery, work & heat recovery

Other tests include:

Low ambient and endurance/controls reliability

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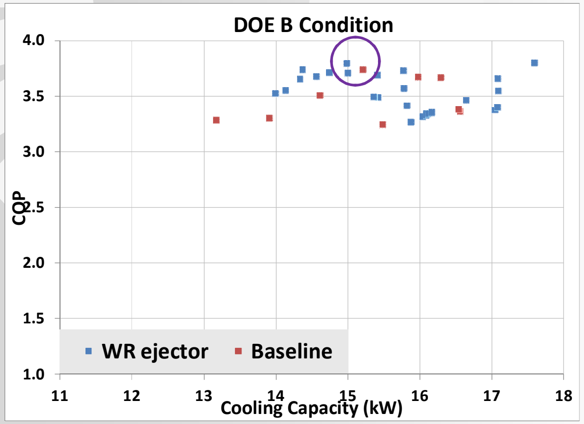
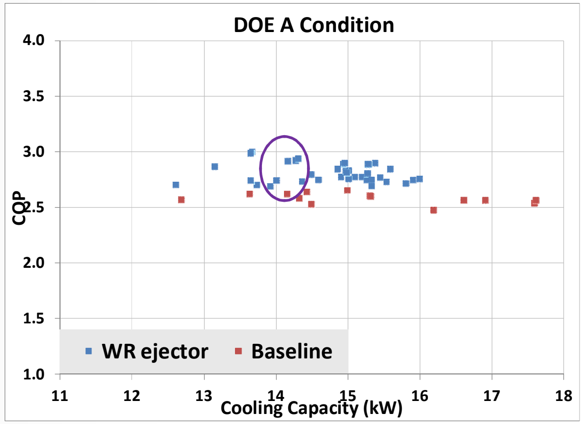
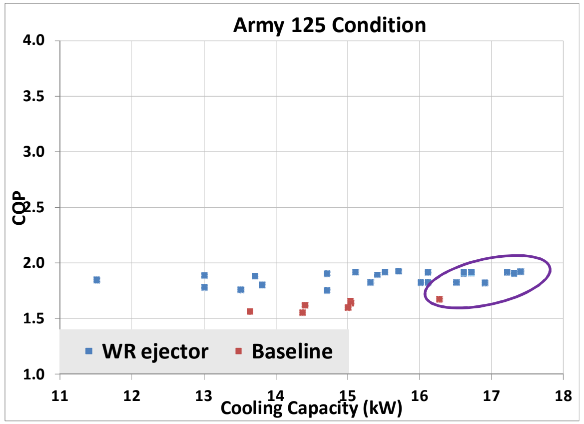
Test Results Summary

Up to 16% improvement in system efficiency demonstrated with work recovery ejector cycle





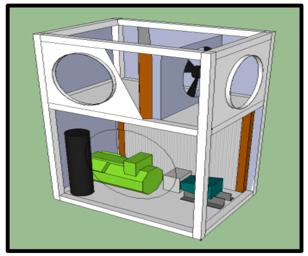


Condition		Cooling (kW)	System Efficiency (COP) Testing (Measured)	
DOE B (82°F)	WR & HR	14.7	3.21	
	WR ejector	15.0	3.80	2% ⇑
	Baseline	15.2	3.74	-
DOE A (95°F)	WR & HR	15.5	2.61*	
	WR ejector	14.3	2.93	11% ⇑
	Baseline	14.4	2.65	-
Army (125°F)	WR ejector	17.4	1.93	16% ⇑
	Baseline	15.0	1.66	-

Performance Metrics

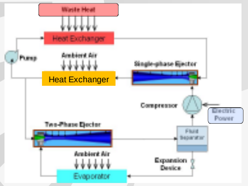
Performance: *Demonstrated 2x COP improvement vs. current ECU but 30% short of target*

Size: *Current ATD comparable to existing ECU but exceeds targets. Optimized ATD weight within target*

Name	**Typical Current ECU**	**Contract Target**	**Current ATD**	**Improved ATD w/o Heat Recovery**
System efficiency @ 125F	~1	2.75	1.93 (measured)	similar to current ATD
Size	39”x28”x72” 45.5 cu ft	36”x36”x48” 36 cu ft	32”x43”x57” 45.4 cu ft	32”x43”x50” 40 cu ft
Weight	<750 lbm	target 600 lbm (stretch 400 lbm)	934 lbm	< 500 lbm
				

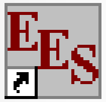
Contract Plan

Demonstrated TRL 5 through advance technology demonstrator system testing



✓ Task 1: Hybrid Cycle Design

✓ Tasks 2&3: 1 and 2-Phase Ejector Modeling (CFD)



✓ Task 4: Reduced-Order Modeling

Q1	2010 Q2	Q3	Q4	2011 Q1	Q2	Q3

✓Contract Signed

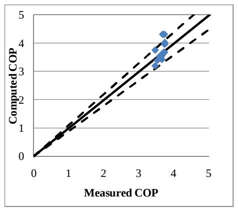
✓Design Review

✓CERDEC Review

✓Final Report And Deliver ATD to Army

✓Task 5: ATD fabrication/commissioning

✓Task 6: Integrated Controls
- ✓ Model based control strategy
- ✓ Develop final control strategy (June. 2011)



✓Task 7: System Testing and Modeling

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